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TITLE OF THE INVENTION

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5 Field of the Invention

10 Description of the Prior Art

Such radio communications systems typically include a broadcast channel (BCH). The BCH is broadcast to all user terminals whether they are registered on the network or not and informs the user terminals about the network. In order to access the network, a user terminal normally tunes to and listens to the BCH before accessing the network. It

25 will then use the information in the BCH to request access to the network. Such a request

typically results in an exchange of information about the network using separate control and access channels and ends in the user terminal receiving an assignment to a particular base station.

Before the user terminal has received an assignment, its request for access is typically sent in a timeslot that is shared with other user terminals. This allows for the possibility that its request will collide with other requests. If the request is received at the same time as the colliding request, it can be difficult to resolve the colliding requests at the base station. However, accurate delay timing advance or delay assignments cannot be made by the base station until the range to each of the user terminals is known. In addition, the BCH does not permit assignments to be made as it is the same for all user terminals that receive it.

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The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings in which like reference numerals refer to similar elements and in which:

5 Figure 1 is a simplified block diagram of a base station on which an embodiment of the invention can be implemented;

Figure 2 is a block diagram of a remote terminal on which an embodiment of the invention can be implemented;

Figure 3 is a diagram of an exemplary broadcast channel BCH burst;

10 Figure 4 is a diagram of an exemplary configuration request CR burst;

Figure 5 is a diagram of an exemplary training sequence in accordance with the present invention;

Figure 6 is a flow chart of an implementation of aspects of the present invention;

Figure 7 is a graph of a search for a least squares error relative timing; and

15 Figure 8 is a graph of a follow-up search for a least squares error relative timing.

DETAILED DESCRIPTION OF THE INVENTION

Base Station Structure

5 The present invention relates to wireless communication systems and may be a fixed-access or mobile-access wireless network using spatial division multiple access (SDMA) technology in combination with multiple access systems, such as time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA). Multiple access can be combined with frequency division
10 duplexing (FDD) or time division duplexing (TDD). Figure 1 shows an example of a base station of a wireless communications system or network suitable for implementing the present invention. The system or network includes a number of subscriber stations, also referred to as remote terminals or user terminals, such as that shown in Figure 2. The base station may be connected to a wide area network (WAN) through its host DSP
15 231 for providing any required data services and connections external to the immediate wireless system. To support spatial diversity, a plurality of antennas 103 is used, for example four antennas, although other numbers of antennas may be selected.

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20 A set of spatial multiplexing weights for each subscriber station are applied to the respective modulated signals to produce spatially multiplexed signals to be transmitted by the bank of four antennas. The host DSP 231 produces and maintains spatial signatures for each subscriber station for each conventional channel and calculates spatial multiplexing and demultiplexing weights using received signal measurements. In this manner, the signals from the current active subscriber stations, some of which may be active on the same conventional channel, are separated and interference and noise

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suppressed. When communicating from the base station to the subscriber stations, an optimized multi-lobe antenna radiation pattern tailored to the current active subscriber station connections and interference situation is created. The same spatial signature is applied to signals received from the user terminal by the base station in order to resolve simultaneous signals on the same channel. Suitable smart antenna technologies for achieving such a spatially directed beam are described, for example, in U.S. Patents Nos. 5,828,658, issued Oct. 27, 1998 to Ottersten et al. and 5,642,353, issued June 24, 1997 to Roy, III et al.

The outputs of the antennas are connected to a duplexer switch 107, which in this TDD system is a time switch. Two possible implementations of switch 107 are as a frequency duplexer in a frequency division duplex (FDD) system, and as a time switch in a time division duplex (TDD) system. When receiving, the antenna outputs are connected via switch 107 to a receiver 205, and are mixed down in analog by RF receiver ("RX") modules 205 from the carrier frequency to an FM intermediate frequency ("IF"). This signal then is digitized (sampled) by analog to digital converters ("ADCs") 209. Only the real part of the signal is sampled. Final down-converting to baseband is carried out digitally. Digital filters can be used to implement the down-converting and the digital filtering, the latter using finite impulse response (FIR) filtering techniques. This is shown as block 213. The invention can be adapted to suit a wide variety of RF and IF carrier frequencies and bands.

There are, in the present example, four down-converted outputs from each antenna's digital filter device 213, one per receive timeslot. The particular number of timeslots can be varied to suit network needs. While the present example uses four

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uplink and four downlink timeslots for each TDD frame, desirable results have also been achieved with three timeslots for the uplink and downlink in each frame. For each of the four receive timeslots, the four down-converted outputs from the four antennas are fed to a digital signal processor (DSP) device 217 (hereinafter "timeslot processor") for further processing, including calibration, according to one aspect of this invention. Four Motorola DSP56303 DSPs can be used as timeslot processors, one per receive timeslot. The timeslot processors 217 monitor the received signal power and estimate the frequency offset and time alignment. They also determine smart antenna weights for each antenna element. These are used in the spatial diversity multiple access scheme to determine a signal from a particular remote user and to demodulate the determined signal.

The output of the timeslot processors 217 is demodulated burst data for each of the four receive timeslots. This data is sent to the host DSP processor 231 whose main function is to control all elements of the system and interface with the higher level processing, which is the processing which deals with what signals are required for communications in all the different control and service communication channels defined in the system's communication protocol. The host DSP 231 can be a Motorola DSP56303. In addition, timeslot processors send the determined receive weights for each user terminal to the host DSP 231. The host DSP 231 maintains state and timing information, receives uplink burst data from the timeslot processors 217, and programs the timeslot processors 217. In addition it decrypts, descrambles, checks error correcting code, and deconstructs bursts of the uplink signals, then formats the uplink signals to be sent for higher level processing in other parts of the base station. With respect to the other parts of the base station it formats service data and traffic data for further higher

processing in the base station, receives downlink messages and traffic data from the other parts of the base station, processes the downlink bursts and formats and sends the downlink bursts to a transmit controller/modulator, shown as 237. The host DSP also manages programming of other components of the base station including the transmit
5 controller/modulator 237 and the RF timing controller shown as 233.

The RF timing controller 233 interfaces with the RF system, shown as block 245 and also produces a number of timing signals that are used by both the RF system and the modem. The RF controller 233 reads and transmits power monitoring and control values, controls the duplexer 107 and receives timing parameters and other settings for each burst
10 from the host DSP 231.

The transmit controller/modulator 237, receives transmit data from the host DSP 231, four symbols at a time. The transmit controller uses this data to produce analog IF outputs which are sent to the RF transmitter (TX) modules 245. Specifically, the received data bits are converted into a complex modulated signal, up-converted to an IF
15 frequency, 4-times over-sampled, multiplied by transmit weights obtained from host DSP 231, and converted via digital to analog converters ("DACs") which are part of transmit controller/modulator 237 to analog transmit waveforms. The analog waveforms are sent to the transmit modules 245.

The transmit modules 245 up-convert the signals to the transmission frequency
20 and amplify the signals. The amplified transmission signal outputs are sent to antennas 103 via the duplexer/time switch 107.

User Terminal Structure

Figure 2 depicts an example component arrangement in a remote terminal that provides data or voice communication. The remote terminal's antenna 45 is connected to a duplexer 46 to permit antenna 45 to be used for both transmission and reception. The antenna can be omni-directional or directional. For optimal performance, the antenna can be made up of multiple elements and employ spatial processing as discussed above for the base station. In an alternate embodiment, separate receive and transmit antennas are used eliminating the need for the duplexer 46. In another alternate embodiment, where time division diversity is used, a transmit/receive (TR) switch can be used instead of a duplexer as is well-known in the art. The duplexer output 47 serves as input to a receiver 48. The receiver 48 produces a down-converted signal 49 which is the input to a demodulator 51. A demodulated received sound or voice signal 67 is input to a speaker 66.

The remote terminal has a corresponding transmit chain in which data or voice to be transmitted is modulated in a modulator 57. The modulated signal to be transmitted 59, output by the modulator 57, is up-converted and amplified by a transmitter 60, producing a transmitter output signal 61. The transmitter output 61 is then input to the duplexer 46 for transmission by the antenna 45.

The demodulated received data 52 is supplied to a remote terminal central processing unit 68 (CPU) as is received data before demodulation 50. The remote terminal CPU 68 can be implemented with a standard DSP (digital signal processor) device such as a Motorola series 56300 DSP. This DSP can also perform the functions of the demodulator 51 and the modulator 57. The remote terminal CPU 68 controls the

receiver through line 63, the transmitter through line 62, the demodulator through line 52 and the modulator through line 58. It also communicates with a keyboard 53 through line 54 and a display 56 through line 55. A microphone 64 and speaker 66 are connected through the modulator 57 and the demodulator 51 through lines 65 and 66, respectively for a voice communications remote terminal. In another embodiment, the microphone and speaker are also in direct communication with the CPU to provide voice or data communications.

The remote terminal's voice signal to be transmitted 65 from the microphone 64 is input to a modulator 57. Traffic and control data to be transmitted 58 is supplied by the remote terminal's CPU 68. Control data 58 is transmitted to base stations during registration, session initiation and termination as well as during the session as described in greater detail below.

In an alternate embodiment, the speaker 66, and the microphone 64 are replaced or augmented by digital interfaces well-known in the art that allow data to be transmitted to and from an external data processing device (for example, a computer). In one embodiment, the remote terminal's CPU is coupled to a standard digital interface such as a PCMCIA interface to an external computer and the display, keyboard, microphone and speaker are a part of the external computer. The remote terminal's CPU 68 communicates with these components through the digital interface and the external computer's controller. For data only communications, the microphone and speaker can be deleted. For voice only communications, the keyboard and display can be deleted.

Broadcast Channel (BCH)

In one embodiment, the system of the present invention is initiated for each user terminal or remote terminal from the broadcast channel BCH which is transmitted as a burst from the base station to all potential user terminals. The BCH burst, unlike the traffic channel bursts, is transmitted in all directions where user terminals may be, typically omnidirectionally but the specific beam pattern will depend on the network. An example of a broadcast burst structure is shown in Figure 3. The BCH communicates enough basic information to enable a subsequent exchange of configuration request CR and configuration message CM between the base station and the user terminal. The BCH also provides general frequency offset and timing update information to all user terminals.

Table 1, below summarizes the content of an example of a BCH burst, as shown in Figure 3.

Broadcast Message	
Field	# of Bits
BStxPwr	5
BSCC	7
BSload	3
Total	15

Table 2

BStxPwr is the effective isotropic radiated power of the broadcast message. This number indicates the power transmitted by the base station taking into account the number of amplifiers and diversity antennas available at the base station.

5 BSCC is the base station color code, used by the user terminal to select training
data for uplink bursts and to distinguish broadcasts of different base stations.

BSload is an indication of the amount of unused capacity the base station has.

In one embodiment, the network is designed to take maximal advantage of spatial division multiple access technologies and particularly smart antenna array signal processing. To help maintain reliable spatial channels in an extremely dense frequency reuse pattern, the network uses time division duplex TDMA where uplink and downlink transmissions are always on the same frequency. In addition, because many user terminals are single antenna and transmit and receive omnidirectionally, except for the BCH, an uplink burst is always received before a downlink burst needs to be sent. This allows downlink bursts to be more accurately spatially directed. An uplink training sequence is embedded in every uplink burst to allow for moderately fast frequency hopping despite any decorrelation of the spatial channel with frequency.

The frequency hopping sequence may be any one of many different sequences well-known in the art. In one embodiment, the parameters of the frequency hopping scheme are initially unknown to the user terminal. This maximizes the flexibility of the network and increases the flexibility of the user terminal. As explained below, the frequency hopping parameters are transmitted to the user in the CM burst.

In one embodiment, the BCH channel is shared by all base stations in the wireless communication system. Using the 7 bit BSCC, up to 128 base stations can be accommodated. The BCH is part of a time division duplex channel with a repeating frame. The channel that includes BCH is a single RF carrier frequency used for uplink and downlink. For high noise environments or for increased robustness, the BCH can hop frequencies according to a predetermined scheme or be repeated on several different frequencies. The repeating frame includes the downlink BCH for each base station, labeled BS1 etc. as shown in Table 3 below. The next frame includes the uplink Configuration Request CR, labeled CR1 etc. and downlink Configuration Message CM, labeled CM1 etc. Each frame also includes a number of reserved slots, shown as empty boxes below. These slots can be used for data traffic, if the broadcast channel is also used for traffic, for other control messages or reserved to reduce interference on other channels in the network. In one embodiment, the other traffic channels hop frequencies around and through the BCH. The frames are repeated for each respective base station 1 to 128 to build a superframe as discussed in more detail below. After the last CM, CM128, the superframe repeats and begins again with the next superframe and the BCH for base station 1.

In another embodiment, the BCH is on its own channel and CR and CM are on a separate control channel. Alternately, one BCH can be provided on a constant frequency and a secondary BCH can be provided on another channel with hopping frequency. The hopping channel is described in the CM.

In one embodiment of the present invention, a session begins when a user terminal seeks to register with a base station. The user terminal does this without knowing its relative position to the best station in terms of direction and distance (or range) to the base station (BS). Therefore, when the user terminal (UT or remote terminal or subscriber station) requests registration using a configuration request (CR) burst, the

base station receives the transmission from the user terminal with a large timing uncertainty and unknown spatial parameters or weights when compared to traffic bursts that already utilize timing advance directives from the base station.

Before registration, several user terminals may transmit CR bursts during the same time slot to register with the same base station. CR bursts addressed to different base stations may also be received. The base station resolves these requests using spatial processing and multiple antennas. By combining the multiple antenna measurements (beamforming) the base station minimizes the interference between signals and maximizes the signal-to-noise ratio (SNR) of each received burst.

Beamforming can be performed in a variety of ways. In one embodiment, a training sequence is used with a least-squares cost function to determine the weights for a beamformer. This allows signals to be classified as desired or undesired. The training sequence-based approach uses an estimation of the timing and frequency offset of the CR burst. This estimation task can be performed by determining the least-squares cost for each timing and frequency hypothesis. This demands great computational resources. Using a special sequence design and a beamforming algorithm that does not require a search over the entire timing uncertainty range alleviates the computational load of the full search. In one embodiment, since CR bursts have a high timing inaccuracy, a periodic training sequence is dedicated for CR bursts alone.

Configuration Request Burst Structure

A configuration request (CR) burst is transmitted by a user terminal (user terminal) in order to initiate communications or registration with a base station (base station). It is transmitted after gathering information about the system by listening to (multiple) broadcast channel (BCH) bursts. The CR burst, is the first communication from a user terminal to the base station and therefore, the user terminal does not have any

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The information symbols of the present CR burst are mapped out as shown in Table 5, below. Any of the items listed below can be deleted and transmitted later during the registration cycle or not at all based on the needs of the system. CR is scrambled by a function of BSCC ensuring that even if there is some interference from CRs sent to nearby base stations, the demodulation capture effect of the BSCC works out any collisions. In one embodiment, the scrambling is performed by taking the encoded bit sequence and exclusive OR'ing it with the output of a linear feedback shift register.

Configuration Request Message	
Field	# of Bits
identity	8
utClass	4
txPwr	5
Total	17

Table 5

identity is a set of unique random bits for each user terminal that differentiate simultaneous messages from multiple user terminals. Because of the randomness and large number of bits, it is unlikely that two user terminals will select the same identity code at the same time.

utClass identifies user terminal capabilities (highest modulation class, frequency hopping capabilities, etc.) This sequence identifies the type of user terminal that sent the CR. A palmtop digital assistant might have different capabilities than a desktop

computer with a fixed dedicated antenna. With utClass, the different capabilities can be distinguished.

txPwr represents the power used by the user terminal to transmit the Configuration Request burst. For example, user terminal power = $(2 \cdot \text{txPwr} - 30)$ dBm.

5 In the present embodiment, the CR burst includes 106 microseconds of extra guard time. As mentioned above, the CR burst is transmitted by a user terminal without any knowledge of the time required for the burst to travel to the base station. In the present embodiment, the desired maximum range from a user terminal to a base station is 15 km. The delay of the burst's reception at the base station includes the delay in
10 receiving the BCH from the base station. A user terminal at range R km receives the BCH burst(s) R/c seconds after they are transmitted by the base station ($c=3 \times 10^8$ m/sec). When the user terminal decides to transmit a CR burst, its signal will be delayed by another R/c seconds, so that the delay of the CR burst at the base station relative to base station time will be $2R/c$ seconds. To accommodate delays created by a maximum range
15 of 15 km, the guard period at the end of the CR burst time slot should be at least 100 microseconds. In addition, in the present embodiment, the user terminal randomly delays its CR burst transmission from 0 to 9 symbols in order to reduce collisions with other user terminals that are sending CR bursts in the same slot and that may be at about the same range from the base station. Therefore, a CR burst from a distant user terminal may
20 arrive at the base station as much as 118 microseconds late as compared to a user terminal that is very close to the base station and that does not delay its CR burst transmission. This accounts for the 106 microseconds of extra guard time that is allotted to the CR burst and the extra margin supplied by the 15 microseconds of inter-burst guard time. With the inter-burst guard time 3 microseconds of extra margin are allotted before
25 the beginning of the next slot.

The present embodiment also includes an additional 15 microseconds of interburst guard time. This helps to confine the RF energy from the CR burst to the time-slot allocated for the CR burst in order not to create adjacent slot interference. The interburst guard time provides a total guard time of 121 microseconds to reduce the likelihood that
5 a CR burst will extend into the next time slot.

The CR burst is sent on the control carrier, as an example, exactly 2265 μ sec after receipt of a downlink BCH burst. In this way, an otherwise uninitialized user terminal can send CR without any knowledge of the frequency hopping sequence parameters. As discussed above, the CR burst is shorter than a standard uplink time-slot to allow for
10 unknown time-of-flight from the user terminal to the base station and typically arrives late in the uplink time-slot receive window.

Training Sequences

15 In the present embodiment, known periodic training sequences are used for the training of base station beamformers in order to extract the desired CR bursts in the presence of interference. The training sequence includes several periodic repetitions of a core sequence followed by a marker sequence. Alternatively, the marker sequence may precede the repetition of the core sequence. By repeating the core sequence, the search
20 range for a least squares (LS) beamformer can be reduced to a single repetition period of the training sequence. The period of the core sequence is a compromise between the duration of the search range and the possibility of finding sequences of the specified period with good autocorrelation and cross correlation properties. In the present embodiment, constraints on the periodicity, mean, autocorrelation and cross correlation
25 are used to define the core sequences of the training sequence for CR burst acquisition.

The bounds on auto and cross correlations help to make delayed versions of these sequences to appear partially uncorrelated to an LS beamformer which resolves them.

The two periodic sequences can be shared among base stations. In one embodiment, depending on its color code, a base station will accept one of the two core training sequences but not both. The user terminal will be able to transmit the correct accepted sequence after learning the base station color code from the broadcast (BCH) burst. This enables a reuse pattern of 2. For reuse patterns greater than 2, some of the constraints on the sequences can be relaxed to yield a larger set of possible periodic sequences to distribute among the base stations.

In an alternate embodiment, the user terminal selects which of the core sequences it will transmit. This can aid a base station in resolving two interfering CR bursts. The core sequence can be selected based on a serial number, product number, ID number or other stored number of the user terminal. For, example if the two sequences s_1 and s_2 above are available, the user terminal can read its serial number register. If the serial number is odd it selects sequence s_1 and if the serial number is even it selects s_2 . In another embodiment, the user terminal can generate a random number from 1 to 2. If there are more than two sequences a greater range of random numbers can be generated. The random number is then mapped into a list of sequences in order to select the periodic sequence that is associated with the generated random number.

Transmitting CR Burst and Random Delay

In one embodiment, the base station transmits broadcast channel (BCH) bursts continuously over a pre-established known channel. To begin a session with a desired base station, an unregistered and unrecognized user terminal in an unknown location listens to the BCH bursts. From the BCH, it determines the base station with which wants to establish communications and selects an appropriate training sequence for that

base station. It also selects a random number D between 0 and 9, and transmits its CR burst after delaying it for D symbols. The number for the delay can be selected as described above with respect to the periodic training sequence. The user terminal can select an internal register such as a Serial No. or Product ID No., that contains a number
5 greater than 9 and use this as a pointer to select the number D . Alternatively, the user terminal can use a random number generator to generate a random number between 0 and 9 and apply this number to select D .

In one embodiment, the maximum value of random delay D is 9 symbols. Therefore, a user terminal can pick one of the 10 random delays, $\{0, 1, 2, \dots, 9\}$ to send its
10 CR burst to the base station. In addition, the maximum allowable roundtrip delay from the base station to the user terminal is assumed to be 50 symbols. Therefore, a CR burst can be delayed as much as 59 symbols for a user terminal at the maximum possible range. This delay is measured with respect to the CR burst of a user terminal that is at zero range and that did not delay its transmission.

15 The base station receives and resolves the CR burst as described below. The roundtrip delay is determined to be $2(R/c) + D$ microseconds (since a symbol period is 2 microseconds where R km is the range of the user terminal. The base station, in the Configuration Message (CM) burst, then instructs the user terminal to advance its time by $\tau_a = (R/c + D/2)$ microseconds in its response to the CR burst. The base station is unaware
20 of what, if any delay D the user terminal has applied to its CR burst. In response to this instruction, the user terminal, knowing its random delay D will subtract out the random delay from the propagation delay and advance its timing by $\tau_a - (D/2)$ microseconds.

The random delay of D symbols is particularly valuable in a microcellular setting, or when user terminals cluster at about the same range from the base station. If the range
25 is about the same for two different user terminals, the CR bursts from the two user terminals will look identical at the base station and may not be resolved. With random delays, the CR bursts will be spaced apart making them easier to distinguish.

CR Burst Resolution

Figure 5 shows a training sequence of a CR burst for one embodiment of the invention. In Figure 5, \mathbf{x} 510 is one of the two core sequences $\{s_1, s_2\}$. \mathbf{x} is the vector consisting of 12 symbols x_1 to x_{12} . In this application, boldface text is used to represent vectors and normal text is used to represent scalars. The complete CR Burst training sequence is constructed from the core periodic sequence \mathbf{x} . Nine repetitions of \mathbf{x} ; P1,P2,..., P9 are followed by a marker sequence M 505. Figure 5 also can be viewed from the perspective of base station timing. In one embodiment, Figure 5 shows windows that the base station uses to resolve received training sequences in a CR burst. In this context, the sequences P1 to M would line up with the windows as shown only if the sequences were received from a user terminal that was in the same location as the base station, or in other words, if there were no propagation delay between the base station and the user terminal. In this paradigm, a round trip delay margin window 520 contains the sequences P1 through P5 for a total of 60 symbols or 120 microseconds. This accommodates a combined delay of 50 symbols due to the round trip propagation delay between the user terminal and the base station and 10 symbols of user terminal selected random delay. A beamformer analysis window 530 contains core sequences P6 through P9 and so is 48 symbols wide. This window will capture 4 periods of \mathbf{x} even if the CR burst is delayed by up to 60 symbols.

Using the observations that fall into the beamformer analysis window, a base station can estimate the delay encountered by the CR burst modulo-12 symbols since each period P1 through P9 is identical and 12 symbols long. In other words, the measurement in the beamformer analysis window will be the same for the delays τ and $\tau + 12$, where $0 \leq \tau < 12$. The marker sequence M at the end of the burst can be used to resolve this modulo-12 ambiguity.

into a single channel 626. With the new single channel, the CR burst is demodulated and read 628. The redetermined weight vector is also used to send a CM (configuration message) burst or other traffic back to the user terminal 630.

5 This processing structure yields accurate beamformer weights that can be used to receive the desired signal without determining perfect timing for the signal. The beamformer weights can also be used to transmit a burst with appropriate spatial directionality and interference and noise suppression back towards the user terminal in the appropriate corresponding downlink slot.

10 Coarse Search for Relative Timing

After the CR burst has been received in each of the antennas of the array 602 and the signals have been stored 604. The system can proceed to determine the relative timing based on the stored measurements 606. In one embodiment, this process is done
15 using a covariance matrix computation and a Cholesky decomposition.

For measurements that lie in the beamforming analysis window assume that measurements are collected at 1.5 times the symbol rate. In this example, the beamforming analysis window is of duration 48 symbols or 4 repetitions or periods of the core sequence. Next, assume that the variable coreSnapPoint points to the first snapshot
20 that is in the beamformer analysis window, and $r(t)$ denotes the snapshot (measurement vector) collected at time t seconds after the start of the CR burst (relative to base station time). The covariance matrix \mathbf{R} can be estimated as follows, where T_{BAW} is the time of the beamforming analysis window:

$$25 \quad \mathbf{R} = \sum_{t \in T_{BAW}} r(t)r^H(t), \quad T_{BAW} = \{t \mid \text{coreSnapPoint} \leq t < \text{coreSnapPoint} + 48\}$$

After computing the covariance matrix \mathbf{R} , a matrix \mathbf{L} can be found such that

Back Substitution: The resulting vector \mathbf{p}_k is applied to solve for an interim vector \mathbf{x}_k for each hypothesis k , where \mathbf{L} is the Cholesky factor as mentioned above:

$$\mathbf{L}\mathbf{x}_k = \mathbf{p}_k$$

5

Then the least-squares (LS) fit for each hypothesis is computed:

$$f_k = f(\tau_k) = \sum_{t \in T_{BAW}} |d(t + \tau_k)|^2 - \mathbf{X}_k^H \mathbf{X}_k$$

Due to the periodicity of the desired signal within the beamforming analysis window, the cross correlation vector computation can be modified to:

$$\mathbf{p}_k = \sum_{t \in T_1} [\mathbf{r}(t) + \mathbf{r}(t + 12) + \mathbf{r}(t + 24) + \mathbf{r}(t + 36)] d^*(t + \tau_k)$$

in which T_1 is a period of the desired signal, i.e.,

$$T_1 = \{ t \mid \text{coreSnapPoint} \leq t < \text{coreSnapPoint} + 12 \}$$

Therefore, the above calculation of the cross correlation vector \mathbf{P}_k costs one-fourth as many multiplies as it would if the core sequence were not a repeated periodic sequence within the training sequence. Finally, the hypothesis with the minimal LS error \mathbf{f}_k is picked. An illustration is presented with respect to Figure 7.

Figure 7 shows the LS cost function on the vertical axis 702 as a function of the time delay τ for the 18 hypotheses on the horizontal axis 704. The horizontal axis is marked in units of $2/3$ of a symbol time in accord with the sampling rate of 1.5 times the symbol rate. The selected best coarse search time delay estimate 706 is shown in Figure 7 at $\tau = 4/3$ symbols. Note that the delay is measured with respect to the nominal time or modulo-12 time at which the CR burst is expected to arrive. This nominal time is named the coreSnapPoint. This simplified computation of the cross correlation vectors \mathbf{p}_k based on the periodicity of the training sequence within the beamforming analysis window yields substantially the same accuracy as a regular cross correlation computation. Any

mismatch of the training sequence in this simplified approach makes only a minimal impact on the performance of the beamformers due to the periodicity of the training sequence.

5 Follow-up Search

Having made a coarse determination of the relative timing 606 a follow-up timing search 608 can be performed. This search has one more LS error calculation. The result of this calculation can be compared to the best LS error from the coarse search.

10 The LS error vector \mathbf{f}_k from the coarse search is treated as a circular buffer and concentration is on the midpoint of the range between the best location from the coarse search (that yielded the minimum LS error) and its neighbor that yielded the next best LS error.

In the coarse search, the following 20 dimensional vectors were formed :

15 **updatedLSValues** = $[f_{18}, f_1, f_2, f_3, f_4, \dots, f_{17}, f_{18}, f_1]$

and

updatedCoarseSearchGrid = $[-2/3, 0, 2/3, 4/3, 3 \frac{1}{3}, 4, \dots, 11 \frac{1}{3}, 12]$

20 Assume that the hypothesis of f_3 ($\tau = 4/3$) (of the current list) was selected by the coarse search procedure (as shown in Figure 5) because $f_3 < f_2 < f_4$. In the follow-up search procedure, the LS error is computed for $\tau = 1$, since this forms the midpoint of the range between the delays corresponding to f_2 ($\tau = 2/3$) and f_3 ($\tau = 4/3$). This is shown graphically in Figure 8.

25 Figure 8 shows the LS cost function 802 as a function of the 18 hypotheses 804 in which the time domain is again sampled at a rate of 1.5 times the symbol rate. The selected best case coarse search time delay estimate 806 is $\tau = 4/3$ symbols. After the

The frequency candidate that maximizes $\text{freqMatch}(m)$ is selected as the frequency estimate, f_{coarse} . Frequency candidates (f_m 's) are in the set:

$$\{-2800, -2000, -1200, -400, 400, 1200, 2000, 2800\}$$

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Alternatively, the frequency uncertainty can be regarded as much less and fewer hypothesis tests can be performed.

More Accurate Beamforming

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Using the frequency and timing estimates τ_{fine} , f_{coarse} , an improved weight vector, $\mathbf{w}_{\text{final}}$ can be determined and applied to the found core sequences to obtain an estimate of the desired burst $\hat{\mathbf{S}}(t)$:

15

$$\hat{\mathbf{S}}(t) = \mathbf{w}_{\text{final}}^H \mathbf{r}(t)$$

20

The more accurate weight vector is obtained by employing $d(t + \tau_{\text{fine}}) \exp(j2\pi f_{\text{fine}} t)$ as the desired signal in the LS error computations. However, if the corresponding LS error is larger than the follow up search based LS error f_0 , the fine timing and frequency estimates are rejected and the estimates are set to $\tau_{\text{fine}} = \tau_0$ and $f_{\text{coarse}} = 0$, which results in $\mathbf{w}_{\text{final}} = \mathbf{w}_0$.

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To further improve the SNR results at high post-copy SNR levels, the search can be performed for a fine frequency estimate around the coarse frequency estimate at locations $f_{\text{coarse}} + [-800, 0, 800]$ using an LS fit to multichannel measurements for $t \in T_{\text{BAW}}$. Such a search can be included to improve the frequency estimation performance for the CR burst demodulator.

Absolute Timing Recovery

Prior to determining the absolute timing, as opposed to relative timing, the more accurate weight vector is applied in order to convert the measurements stored from each of the antennas into a single channel measurement 620. This conversion is still done using the data in the beamforming analysis window because only this data is certain to consist only of periods of the core sequence. An appropriate procedure 622 for determining the absolute delay can be implemented as follows. Assume that the modulo-12 time-delay estimate is τ , and that $g(t)$ denotes the output of a beamformer (as described above $g(t)$ is a single channel measurement) that extracts the desired CR burst. First, the candidate starting locations for the concatenated sequence [P9,M] (see Figure 5) for each of the five delay hypotheses is determined. For example, if the absolute delay equals τ , the sequence [P9,M] should start $\tau + 36$ symbols away from the left border of the beamformer analysis window. For the hypothesis in which the absolute delay is assumed to be equal to $\tau + 48$, the sequence [P9, M] should start $\tau + 84$ symbols away from the left border of the analysis window.

More specifically, assume that T_k denotes the begin time for the k -th hypothesis, i.e., $T_k = \tau + 36 + (12 \times k)$, for $k=0,1,2,3,4$. Let \mathbf{v}_k denote the samples of $g(t)$ that correspond to the interval which starts at T_k for a duration of 24 symbols (two periods). For each

hypothesis, compute:

$$h(k) = |\mathbf{v}_k [\mathbf{x}, -\mathbf{x}]^H|^2.$$

Pick the hypothesis that yields the maximum $h(k)$.

Assume that hypothesis k_0 is selected. Then, the absolute timing estimate is determined as $\tau + (k_0 \times 12)$.

Due to the orthogonal nature of $[\mathbf{x}, \mathbf{m}]$ and $[\mathbf{x}, \mathbf{x}]$, there is a five-ary pulse-position modulation (PPM) demodulation problem in which the SNR changes depending on the true position of the desired vector $[\mathbf{x}, \mathbf{m}]$. For example, if the actual delay is less than a

period, then the payload portion of the desired CR burst will appear as noise for the hypothesis tests 1,2,3,4. On the other hand, if the actual delay is, for example 20 symbols, then, the CR burst payload symbols will not contribute to the test of a hypothesis in which $k=0$ as noise because of the orthogonality of $[\mathbf{x}, \mathbf{m}]$ and $[\mathbf{x}, \mathbf{x}]$, but they will contribute to the noise component in $h(k)$ for $k=2,3,4$. With this delay condition, the beamforming analysis window receives the following 48 symbols:

$$x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_1, x_2, x_3, x_4, \dots x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_1, x_2, x_3, x_4,$$

In this stream, the first and last 12 symbols are written out. The spatial processing search will discover the first occurrence of x_1 at a delay of 8 symbols. The next step is to determine whether the absolute delay is 8,20,32,44,56 symbols. In order to determine this, the measurements following the beamforming analysis window are focused upon. With a delay of 20 symbols, the next 40 symbols will be:

$$x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, -x_1, -x_2, -x_3, -x_4, \\ -x_5, -x_6, -x_7, -x_8, -x_9, -x_{10}, -x_{11}, -x_{12}, d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8$$

in which d_i indicates the i -th payload symbol, which is unknown. As a result, $\mathbf{v}_0 = [\mathbf{x}, \mathbf{x}]$ and $\mathbf{v}_1 = [\mathbf{x}, -\mathbf{x}]$, which results in $h(0)=0$ and $h(1) = 24^2$. Accordingly, the desired signal does not contribute to the decision variable $h(0)$ when the absolute delay is larger than 12. On the other hand, $\mathbf{v}_2 = [-x_1, -x_2, \dots, -x_{12}, d_1, d_2, \dots, d_{12}]$ is not necessarily equal to zero. The first half of \mathbf{v}_2 equals the marker sequence, which yields the result:

$$h(2) = |-12 - [d_1, d_2, \dots, d_{12}] \mathbf{x}^H|^2.$$

This differs significantly from:

$$h(3) = |[d_1, d_2, \dots, d_{12}] \mathbf{x}^H - [d_{13}, d_{14}, \dots, d_{24}] \mathbf{x}^H|^2.$$

$h(2)$ is expected to be higher than $h(3)$ on average because of the coherence term (-12) inside the magnitude operator and its presence creates a significant competition to the correct hypothesis decision value ($h(0)$) in the presence of measurement noise.

Therefore, absolute delay errors that are equal to +12 should dominate other values of

delay estimation errors. One way to eliminate the self-noise problem is to put the marker sequence in the beginning of the burst and search for the concatenated sequence $[-\mathbf{x}, \mathbf{x}]$. In such a design, self noise will exist only due to the presence of the ramp-up symbols, but this will affect the noise component in only one of the $h(k)$'s. Other modifications to the ordering of the sequences are also possible to suit particular applications.

As discussed above, the remaining task is to find the marker sequence. This can be done based on a cross correlation operation with the 1.5 times over-sampled version of the sequence $[\mathbf{x}, -\mathbf{x}]$ with \mathbf{v}_k corresponding to all of the five hypotheses locations indicating period slips of 0,1,2,3,4.

Using the fine timing estimate τ_{fine} , the time of the final beamformer output sample (that arrives at t_c) which is closest to $\text{coreSnapPoint} + \tau_{\text{fine}}$ is determined. Let τ_e denote the time difference between the chosen measurement at t_c and the location of actual timing location:

$$\tau_e = t_c - \text{coreSnapPoint} - \tau_{\text{fine}}$$

Remember that the beginning of the k -th hypothesis ($k=0,1,2,3,4$) will be at times $T_k = \text{coreSnapPoint} + \tau_{\text{fine}}$. Therefore, the vector \mathbf{v}_k to be tested for the cross correlation for the k -th hypothesis will take the form:

$$\mathbf{v}_k = [\hat{S}(t_c + 12 \times (3 + k)), \hat{S}(t_c + 12 \times (3 + k) + 2/3), \hat{S}(t_c + 12 \times (3 + k) + 2 \times 2/3), \dots, \hat{S}(t_c + 12 \times (3 + k) + 35 \times 2/3)]$$

which is a vector with 36 entries.

The \mathbf{v}_k 's are cross correlated with the desired signal vector \mathbf{d} , which is formed from the knowledge of the training waveform and the timing difference τ_e :

It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form.

The present invention includes various steps. The steps of the present invention may be performed by hardware components, such as those shown in Figures 1 and 2, or may be embodied in machine-executable instructions, which may be used to cause a general-purpose or special-purpose processor or logic circuits programmed with the instructions to perform the steps. Alternatively, the steps may be performed by a combination of hardware and software. The steps have been described as being performed by either the base station or the user terminal. However, any steps described as being performed by the base station may be performed by the user terminal and vice versa. The invention is equally applicable to systems in which terminals communicate with each other without either one being designated as a base station, a user terminal, a remote terminal or a subscriber station.

The present invention may be provided as a computer program product which may include a machine-readable medium having stored thereon instructions which may be used to program a computer (or other electronic devices) to perform a process according to the present invention. The machine-readable medium may include, but is not limited to, floppy diskettes, optical disks, CD-ROMs, and magneto-optical disks, ROMs, RAMs, EPROMs, EEPROMs, magnet or optical cards, flash memory, or other type of media / machine-readable medium suitable for storing electronic instructions. Moreover, the present invention may also be downloaded as a computer program product, wherein the program may be transferred from a remote computer to a requesting computer by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

Importantly, while the present invention has been described in the context of a wireless internet data system for portable handsets, it can be applied to a wide variety of

different wireless systems in which data are exchanged. Such systems include voice, video, music, broadcast and other types of data systems without external connections.

The present invention can be applied to fixed remote terminals as well as to low and high mobility terminals. Many of the methods are described in their most basic form but steps

5 can be added to or deleted from any of the methods and information can be added or.

subtracted from any of the described messages without departing from the basic scope of the present invention. It will be apparent to those skilled in the art that many further modifications and adaptations can be made. The particular embodiments are not provided to limit the invention but to illustrate it. The scope of the present invention is

10 not to be determined by the specific examples provided above but only by the claims
below.

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